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# **Middle Strat (25km) and Lower Trop (2.2km) CO<sub>2</sub> from AIRS (progress toward satellite retrieval of a profile)**

**Mous Chahine, Edward Olsen, Luke Chen, Tom Pagano,  
Xun Jiang and Yuk Yung**

**NOAA Hyperspectral  
Spectrometer Workshop**

**March 29 - 31, 2011**

**Miami Florida**



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# The Atmospheric Infrared Sounder on NASA's EOS Aqua Spacecraft

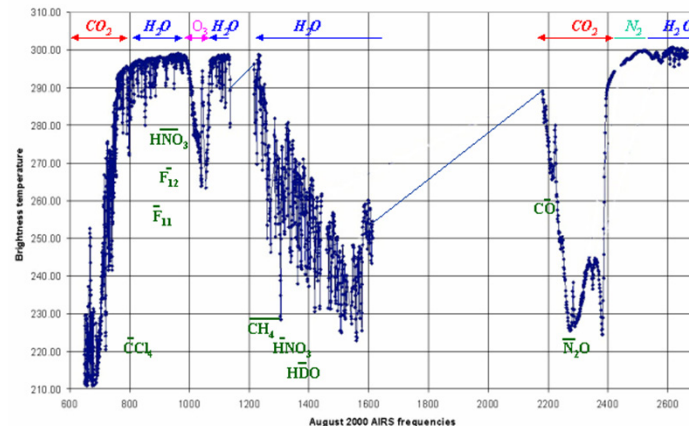
- AIRS Characteristics
- Launched: May 4, 2002
- Orbit: 705 km, 1:30pm, Sun Synch
- IFOV :  $1.1^\circ \times 0.6^\circ$   
(13.5 km x 7.4 km)
- Scan Range:  $\pm 49.5^\circ$
- Full Aperture OBC Blackbody,  $\varepsilon > 0.998$
- Full Aperture Space View
- Solid State Grating Spectrometer
  - IR Spectral Range:  
3.74-4.61  $\mu\text{m}$ , 6.2-8.22  $\mu\text{m}$ ,  
8.8-15.4  $\mu\text{m}$
  - IR Spectral Resolution:  
 $\approx 1200 (\lambda/\Delta\lambda)$
  - # IR Channels: 2378 IR
- VIS Channels: 4
- Mass: 177Kg,  
Power: 256 Watts,  
Life: 5 years (7 years goal)
- Built: BAE Systems

## AIRS



## AIRS Spectra

AIRS Channels for Tropical Atmosphere with  $T_{\text{surf}} = 301\text{K}$   
Full Spectrum





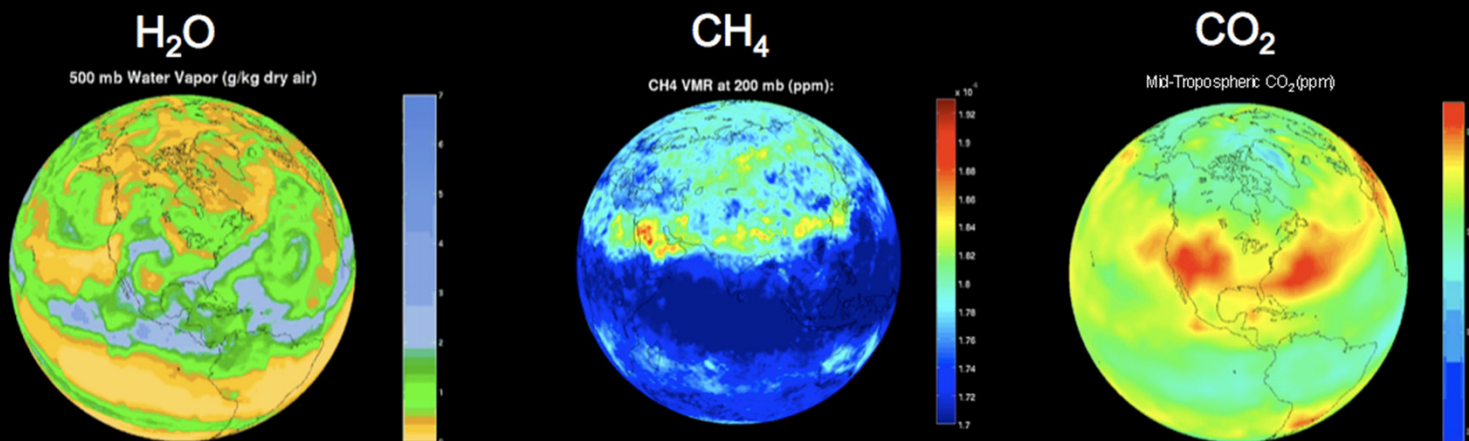
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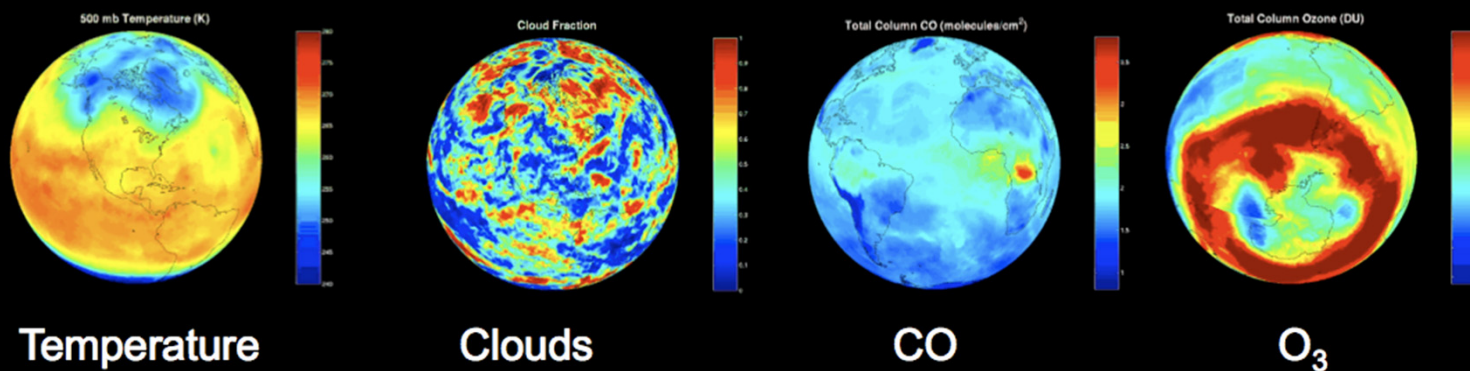
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# AIRS Products for Weather, Climate and Composition

## AIRS Greenhouse Gases



## Other AIRS Atmospheric Climate Products





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## 3 Layers of CO<sub>2</sub> Derived from AIRS

**Current Status**

Task	Mid-Troposphere	Stratosphere	Lower Troposphere
Algorithm Development	✓	✓	✓
Initial Channel Selection			
Retrieval Optimization	✓	✓	✓
Beta Software Development & Test			
Refine Channel Selection			
Refine Quality Control			
Validation and Comparison	✓*	In progress	In progress
In-Situ Measurements			
Models			
Report Results	✓		
Professional Meetings			
Journal Publications			
Transition to Operational Stage	✓		
Production Software Development			
Documentation			
Production	✓		
Distribution via GES DISC & JPL	✓*		

\*Continuous Updates





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## The Method of Vanishing Partial Derivatives Finding the LOCAL minimum on an N-Dimensional Surface According to Gauss

The CO<sub>2</sub> retrieval is a post-processing algorithm applied after AIRS Level-2 product generation:

**Local Minimum:**  $\Theta_M, T^0(p), q^0(p), O_3^0(p), E_s^0(v)$

$$G^{(n)}(\mathbf{X}) = \sum_v \left[ \Theta_M(\mathbf{X}, v) - \Theta_C^{(n)}(\mathbf{X}, v) \right]^2$$

$$\frac{\partial G}{\partial X_{CO_2}} \rightarrow 0$$

$$\frac{\partial G}{\partial X_{T(p)}} \rightarrow 0$$

$$\frac{\partial G}{\partial X_q} \rightarrow 0$$

$$\frac{\partial G}{\partial X_{O_3}} \rightarrow 0$$

$$\frac{\partial G}{\partial X_{E_s}} \rightarrow 0$$

Satisfying the partial derivatives **individually** provides the necessary and sufficient condition for an extremum of  $G(\mathbf{X})$ . Ascertaining that the extremum is a (local) *minimum* is the result of requiring that  $G$  decreases monotonically with each iteration.

**Caveats:**  $X_i$  are assumed to be independent variables, the completeness of the variable set, the minimum found is not global, and the non-commutative averaging of variations of the variables within data pixels does not lead to significant errors

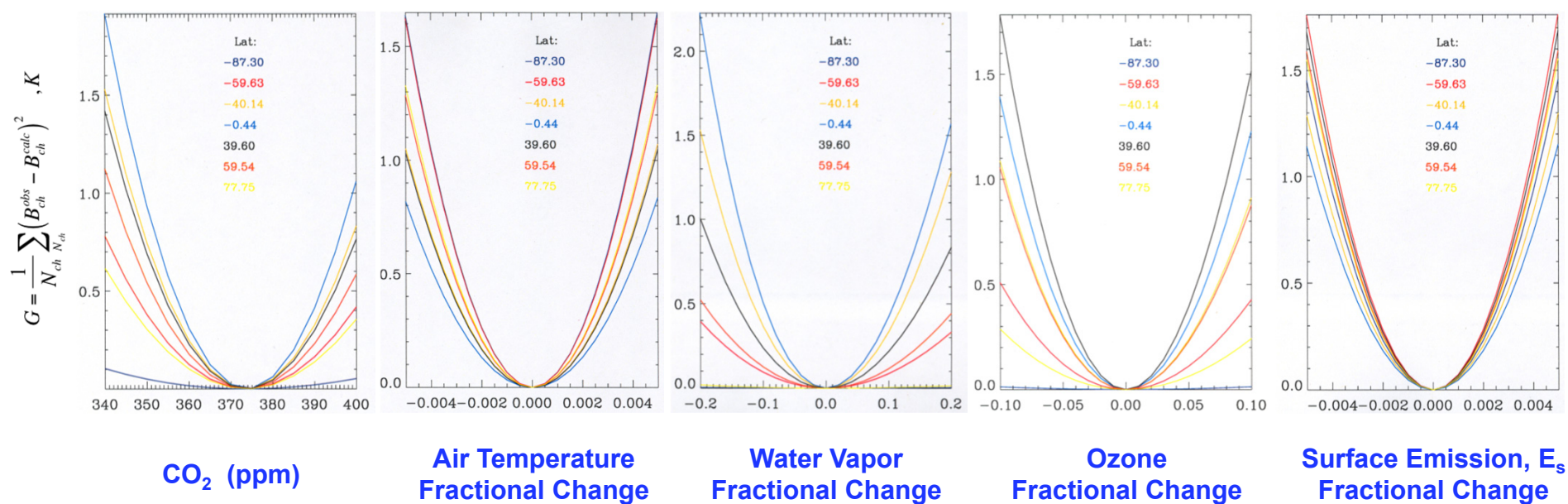


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# The Local Minimum is Well Defined



**Reference:** M. Chahine, C. Barnet, E. T. Olsen, L. Chen and E. Maddy "On the Determination of Atmospheric Minor Gases from the Residuals of the Solution of the Radiative Transfer Equation". *Journal of Geophysical Research Letters*, Vol. 32, November 2005.



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# **AIRS Operational Product Mid-Tropospheric CO<sub>2</sub> (8-10km)**



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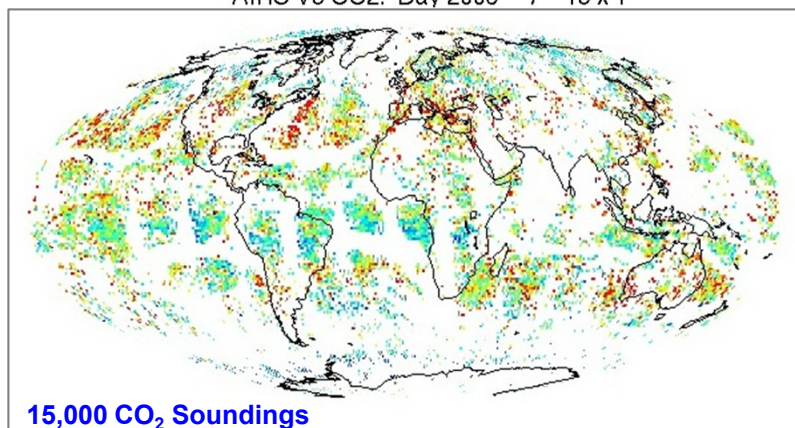
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## Global Yield of AIRS Level 2 Mid-Tropospheric CO<sub>2</sub>

**AIRS Daily CO<sub>2</sub> Yield**  
**1°x1° Spatial Resolution**

AIRS V5 CO2: Day 2003 7 15 x 1

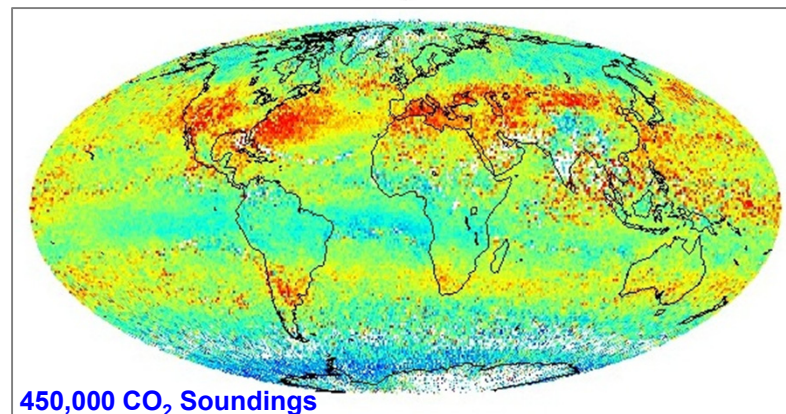


15,000 CO<sub>2</sub> Soundings



**AIRS Monthly CO<sub>2</sub> Yield**  
**1°x1° Spatial Resolution**

AIRS V5 CO2: Day 2003 7 15 x 30



450,000 CO<sub>2</sub> Soundings



AIRS Level 2 Mid-Tropospheric CO<sub>2</sub> retrieval yield is controlled by requirement for highest quality temperature and water vapor AIRS Level 2 products in 2x2 array of adjacent FOVs

**Day/Night, Pole-to-Pole, Land/Ocean/Ice, Cloudy/Clear**





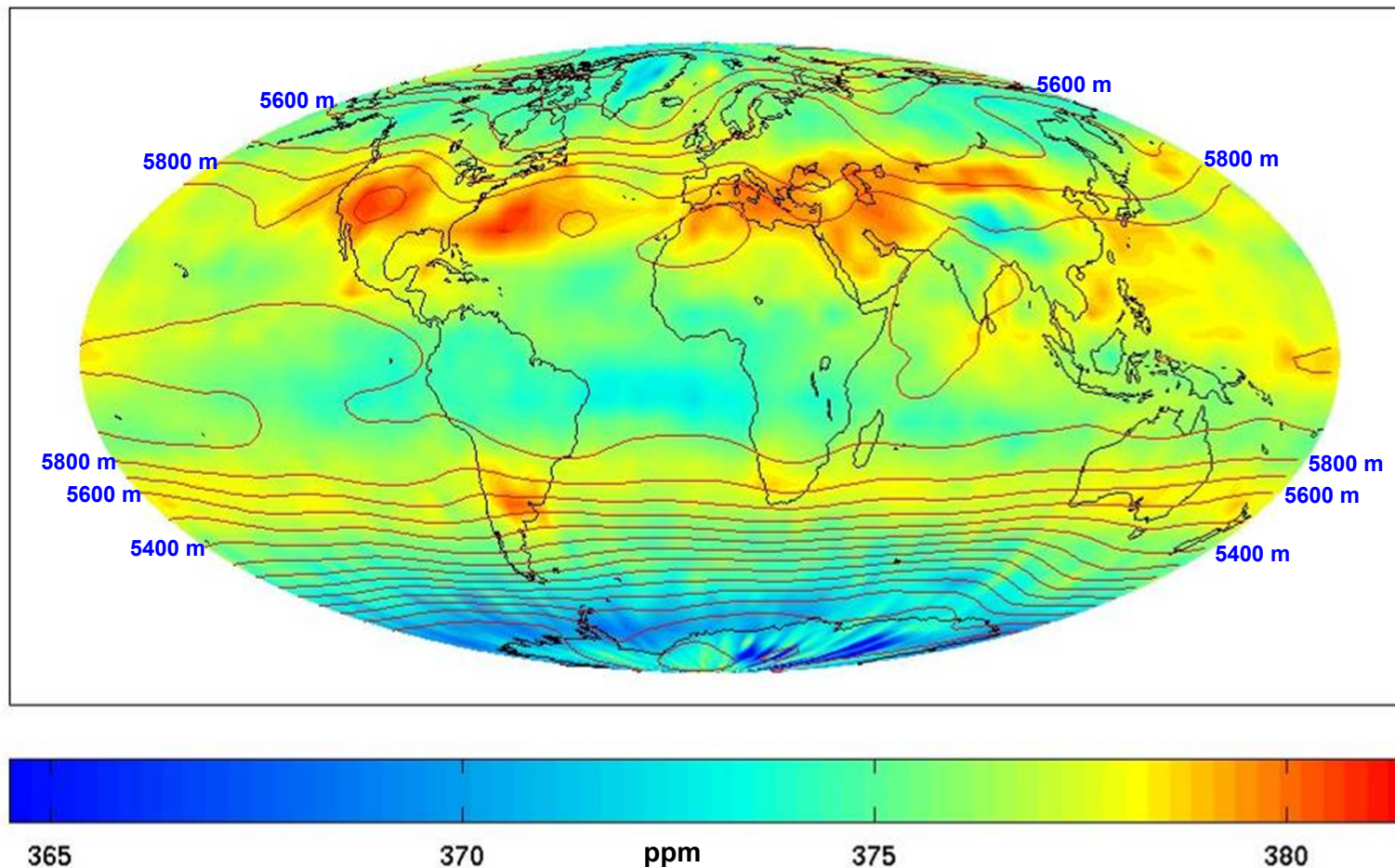
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## AIRS Data Show CO<sub>2</sub> is not well mixed in Mid-Troposphere

*July 2003 AIRS mid trop CO<sub>2</sub> (5° smoothing) with 500 hPa gph contours*



**CO<sub>2</sub> is NOT Well Mixed in the mid-troposphere**

- Driven by synoptic-scale phenomena (polar/subtropical jet streams)
- Complexity of the Southern Hemisphere not present in models
- AIRS mid-trop data will facilitate modeling of vertical & horizontal transport



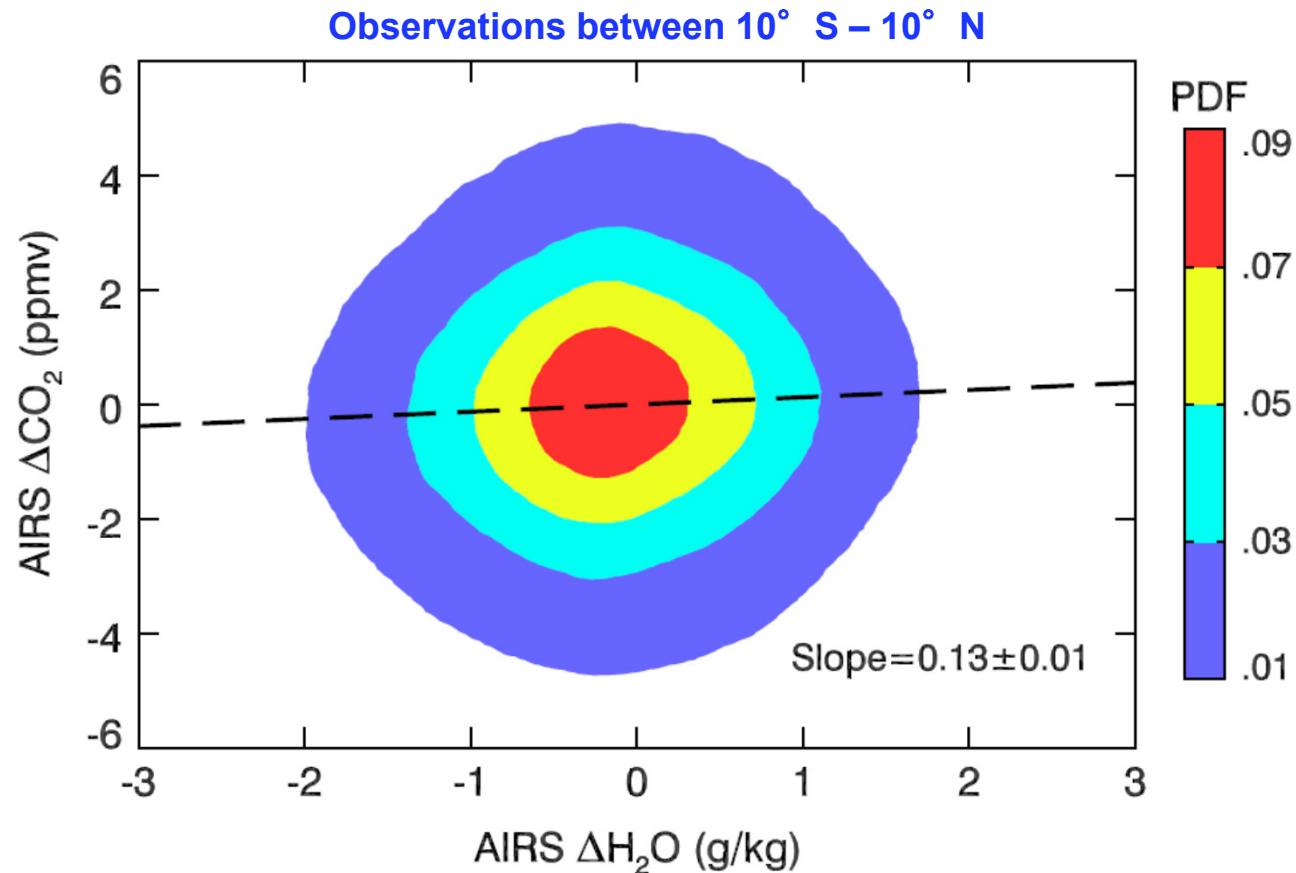
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## Small Bias due to H<sub>2</sub>O Absorption

- **If MJO Amplitude of H<sub>2</sub>O at 600 hPa  $\approx 1.4$  g/kg**  
[Tian et al. (2006), Vertical moist thermodynamic structure and spatial-temporal evolution of the MJO in AIRS observations, J. Atmos. Sci., 63, 2462]
- **Then Potential Bias in CO<sub>2</sub>  $\approx 1.4 \times 0.13 < 0.2$  ppm**



King-Fai Li, Tian, B., Waliser, D.E. and Yung, Y.L. (2010), Tropical mid-tropospheric CO<sub>2</sub> variability driven by the Madden-Julian Oscillation, PNAS, 107 (45), 19171-19175, doi: 10.1073/pnas.1008222107





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## Lack of Correlation in the AIRS VPD Retrievals Among CO<sub>2</sub>, T, H<sub>2</sub>O and O<sub>3</sub>

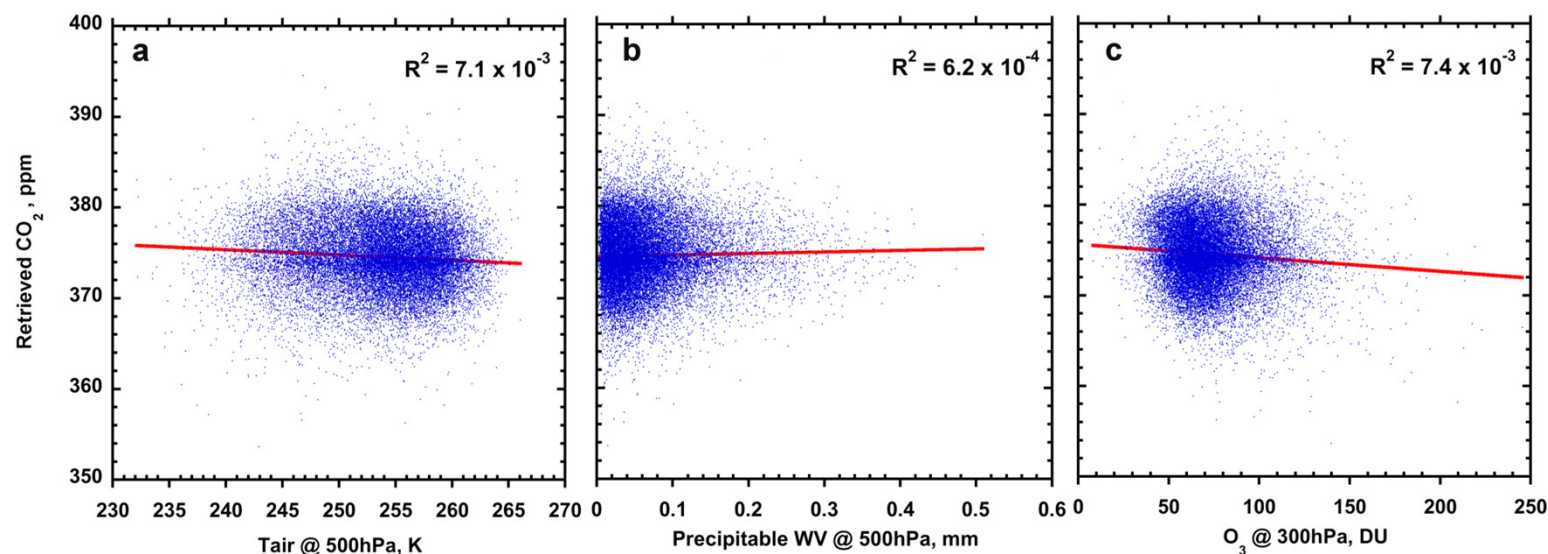


Figure demonstration of lack of correlation among the VPD solutions for 24,635 retrievals of CO<sub>2</sub> and (a) T(500 hPa); (b) H<sub>2</sub>O(500 hPa); (c) O<sub>3</sub>(300 hPa) during January 2003 in the latitude band 30N to 40N. R<sup>2</sup> represents the portion of the variance in CO<sub>2</sub> that could be explained by the variance in the other parameter and is less than 0.8% in all cases.

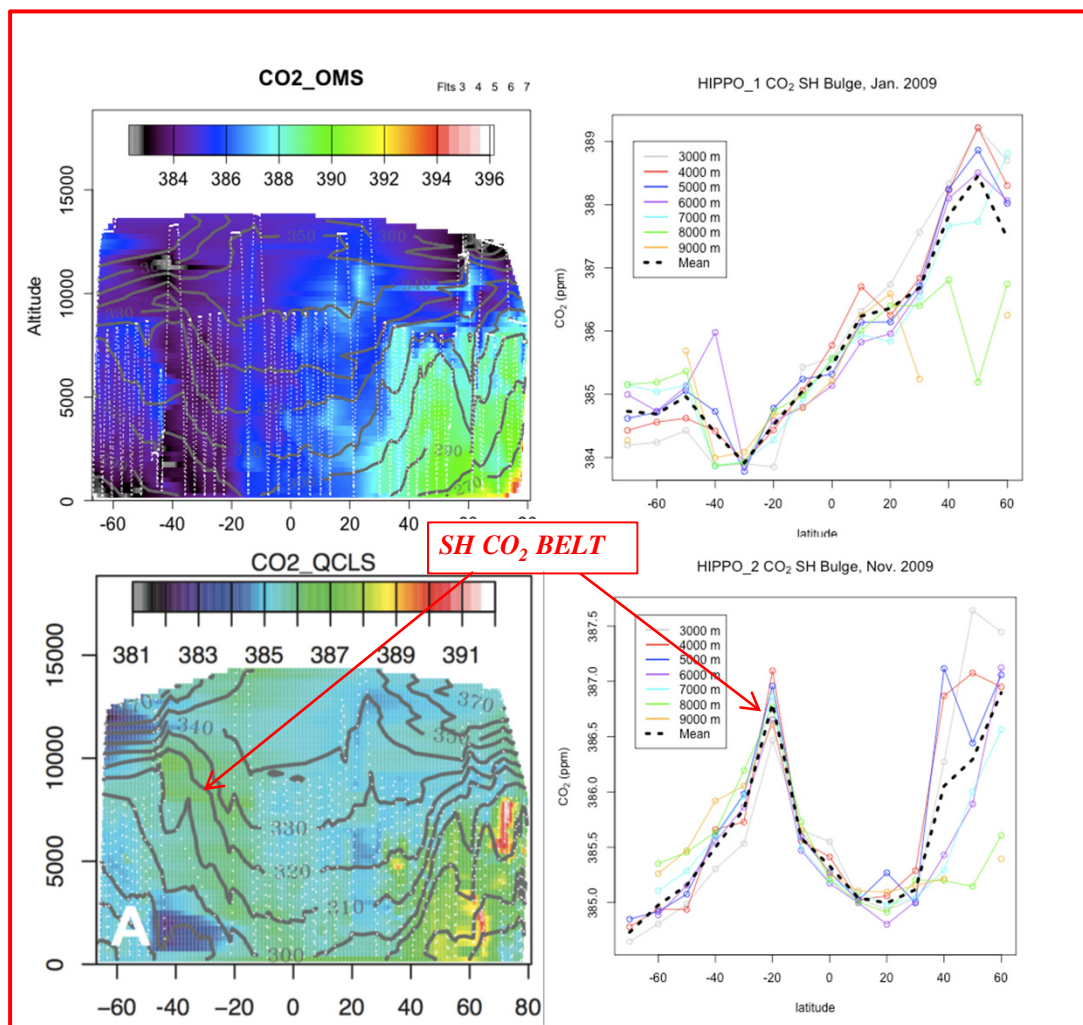


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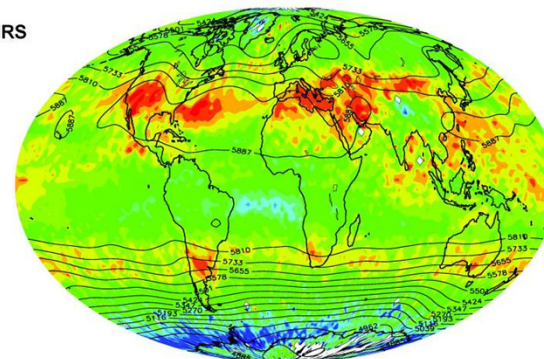
# Variability seen in 2009 HIPPO Campaign Compares well with AIRS



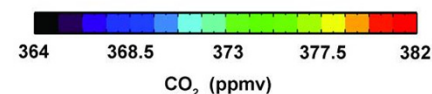
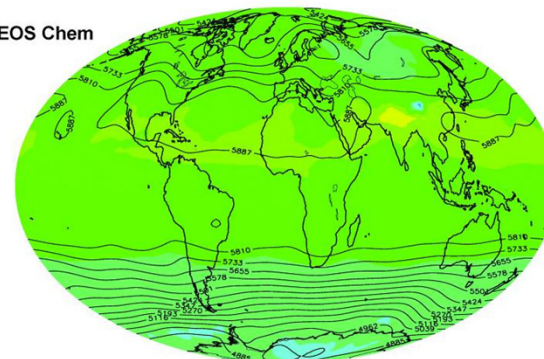
S.C. Wofsy, et al (2011), HIAPER Pole-to-Pole Observations (HIPPO): Fine grained, global scale measurements of climatically important atmospheric gases and aerosols, *Proceedings of the Royal Society A*, in press.

AIRS has observed a  
seasonally-variable  
SH CO<sub>2</sub> Belt Since 2003

AIRS



GEOS Chem



M.T. Chahine, et al., Satellite remote sounding of mid-tropospheric CO<sub>2</sub>, *Geophys. Res. Lett.*, 35, L17807, doi:10.1029/2008GL035022.



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## **AIRS Developing Product Mid-Stratospheric CO<sub>2</sub> (25km)**





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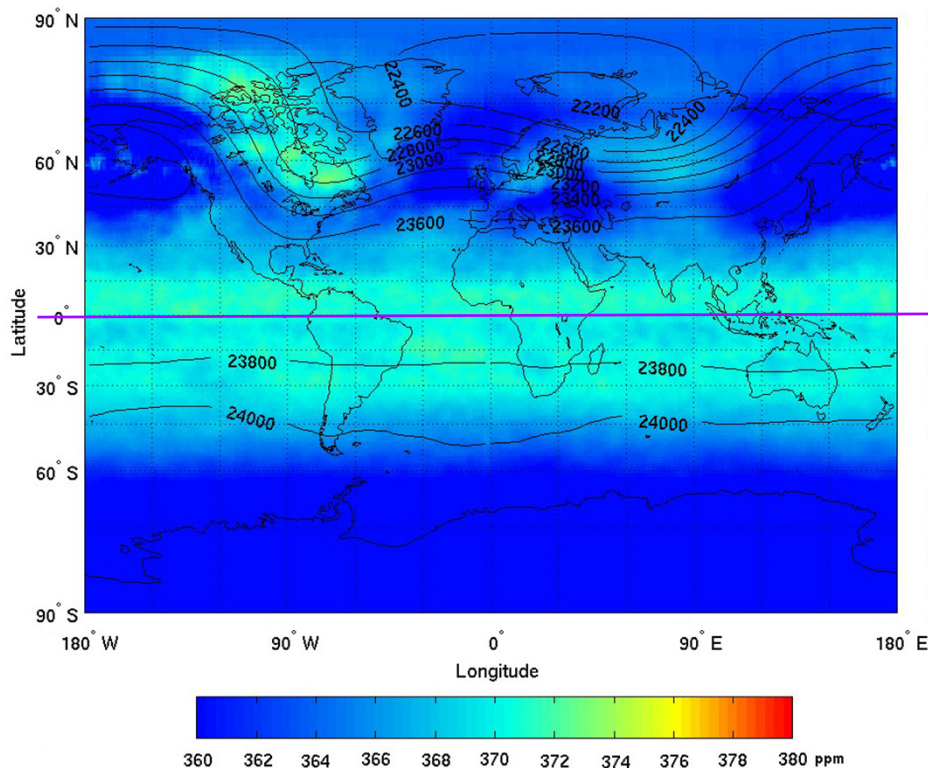
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# Jan 2003 Stratospheric CO<sub>2</sub> Retrieval Compared to Models

(AIRS Stratospheric Contribution Function Applied to Models)

AIRS Retrieved CO<sub>2</sub>

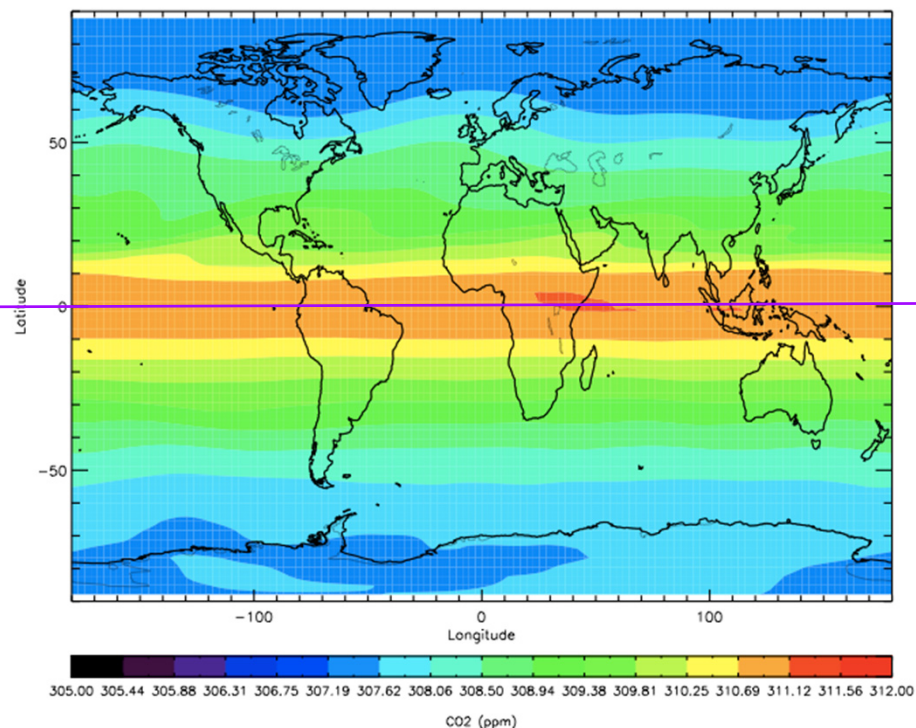


360

Contours are 30 hPa GPH

380

3-D IMATCH CO<sub>2</sub>



305

Model profile weighted  
by AIRS sensitivity function

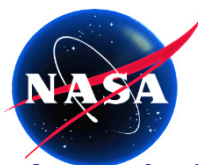
312

**PRELIMINARY**

Both AIRS and models show presence of tropical pipe

- AIRS shows greater variation with latitude (~15 ppm vs ~4 ppm)
- AIRS shows additional troposphere intrusion at high latitude

Model Runs by Xun Jiang, University of Houston



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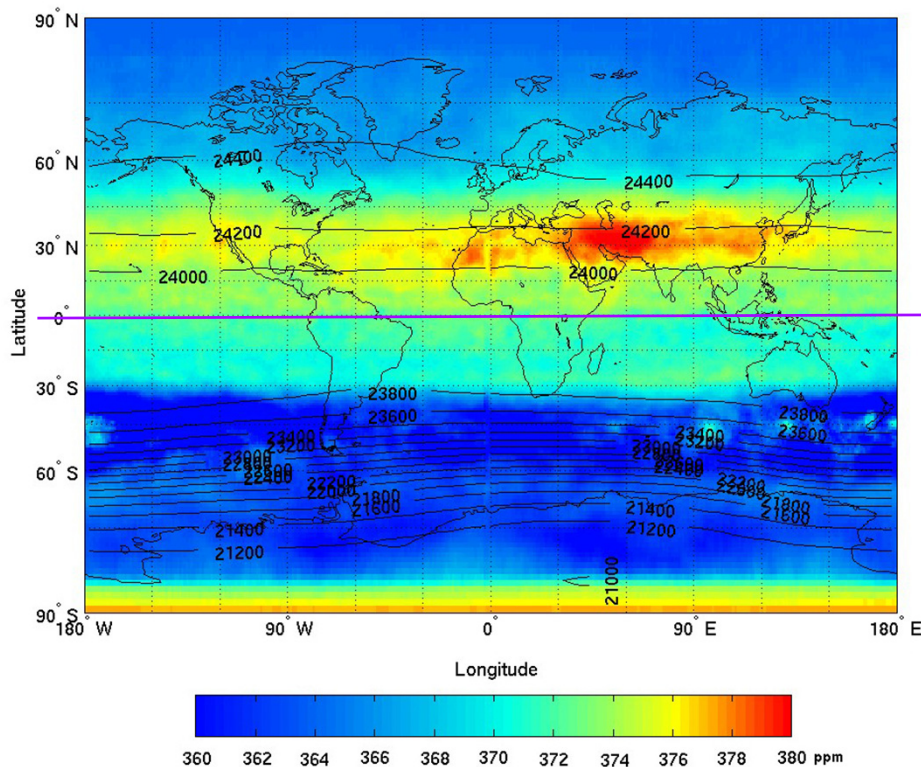
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# Jul 2003 Stratospheric CO<sub>2</sub> Retrieval Compared to Models

(AIRS Stratospheric Contribution Function Applied to Models)

AIRS Retrieved CO<sub>2</sub>



360

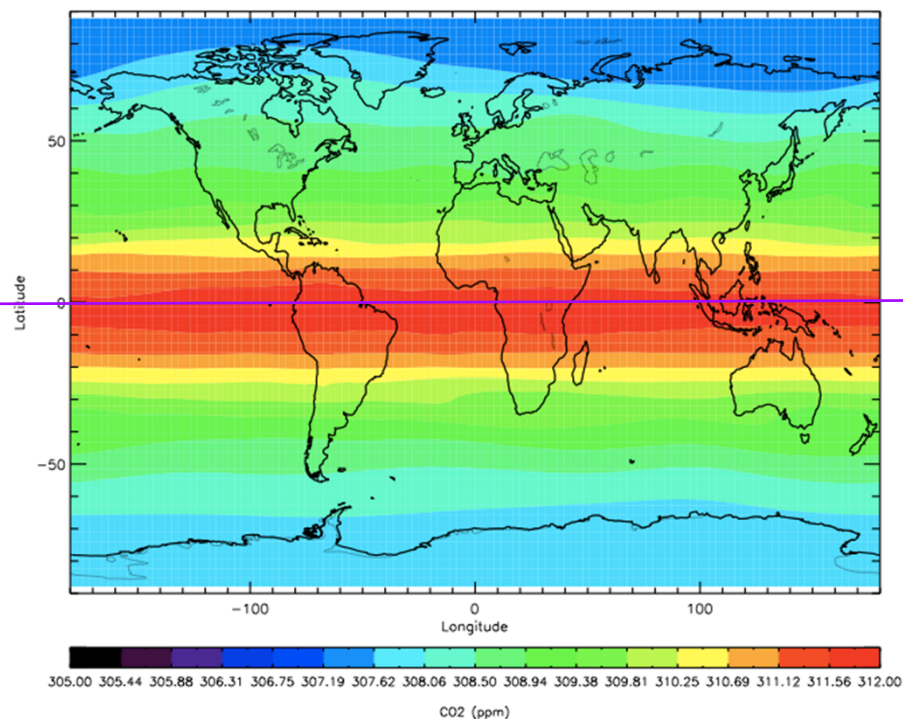
Contours are 30 hPa GPH

380

**PRELIMINARY**

- AIRS tropical Pipe shifts northward in July whereas model tropical pipe remains unchanged
- AIRS shows greater variation with latitude (~15 ppm vs ~4 ppm)

3-D IMATCH CO<sub>2</sub>



305

Model profile weighted  
by AIRS sensitivity function

312





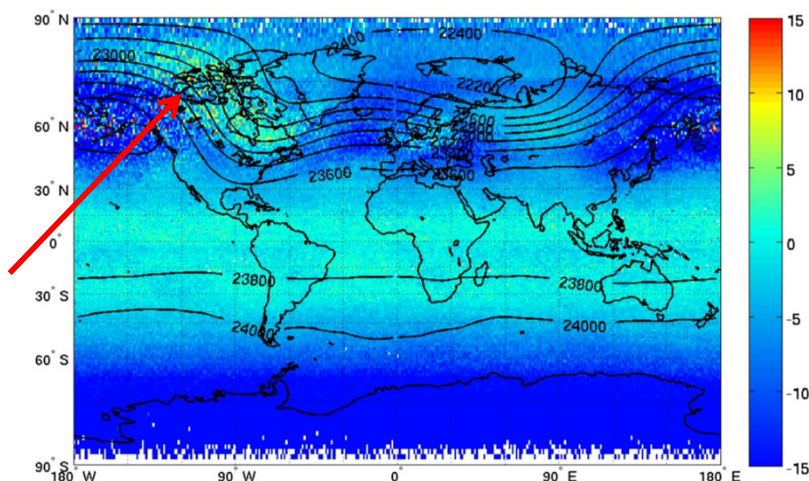
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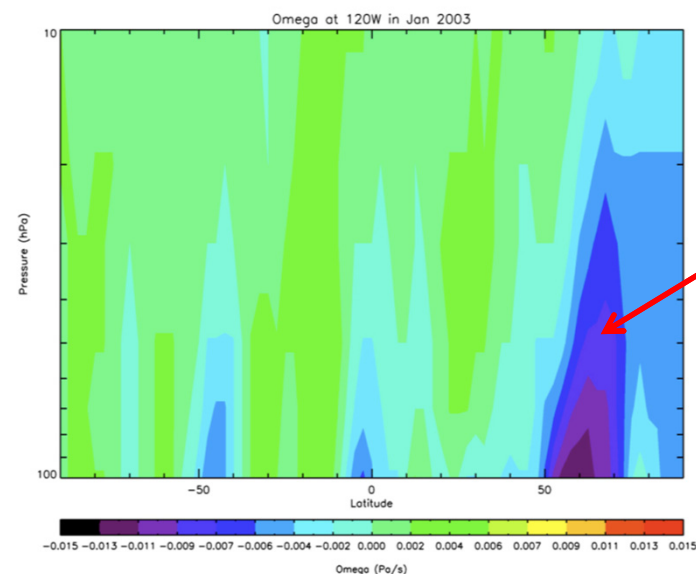
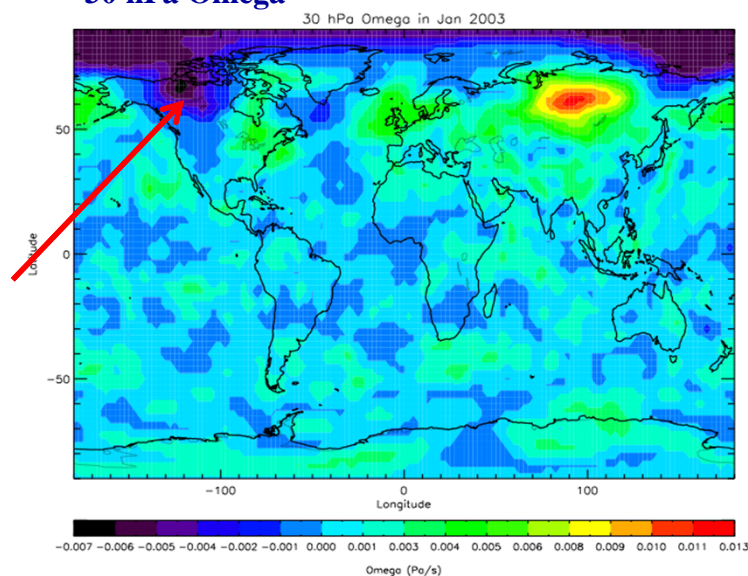
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## AIRS Stratospheric CO<sub>2</sub> (tropospheric CO<sub>2</sub> intrusion/vertical wind)

**AIRS CO<sub>2</sub> for January, 2003**



**30 hPa Omega**



**Vertical velocity ( $dP/dt$ ) at 120°W in January 2003  
(NCEP2 Reanalysis)**

Negative (positive) value represents upward (downward)  
motion. Units are Pa/s.

**Omega =  $dP/dt$  at 30 hPa (NCEP2 Reanalysis)**  
Negative Omega --- Upward motion;  
Positive Omega --- Downward motion





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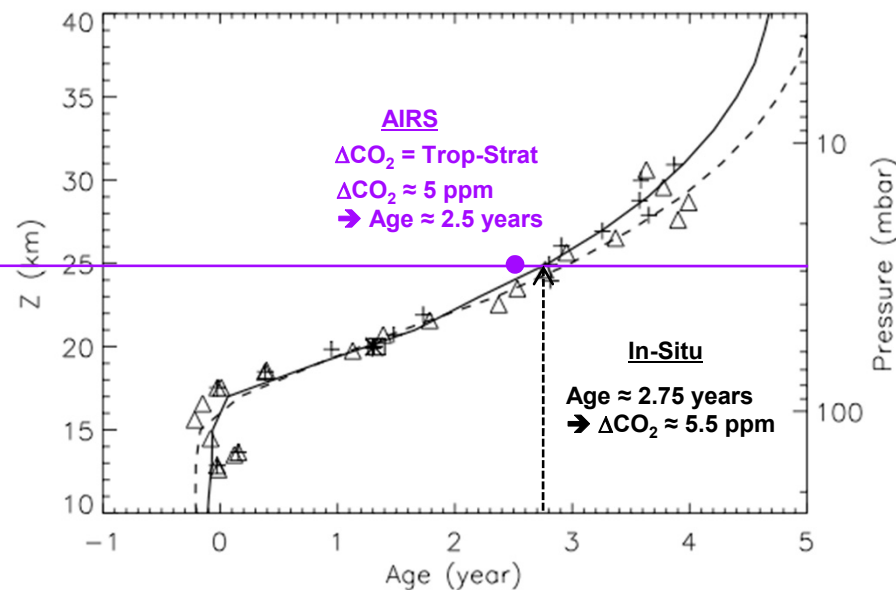
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## CO<sub>2</sub> Trop-Strat Contrast due to Age of Stratospheric Air

Hall et al (1999), Evaluation of transport in stratospheric models, JGR., 104, 18815

Altitude of maximum of  
AIRS Contribution Function



Age of stratospheric air vs altitude  
for  $|\text{latitude}| \leq 10^\circ$

The concentration of CO<sub>2</sub> in the stratosphere will be lower than in the troposphere by ~ 2 ppm for each year it lags behind due to interannual growth of tropospheric CO<sub>2</sub>



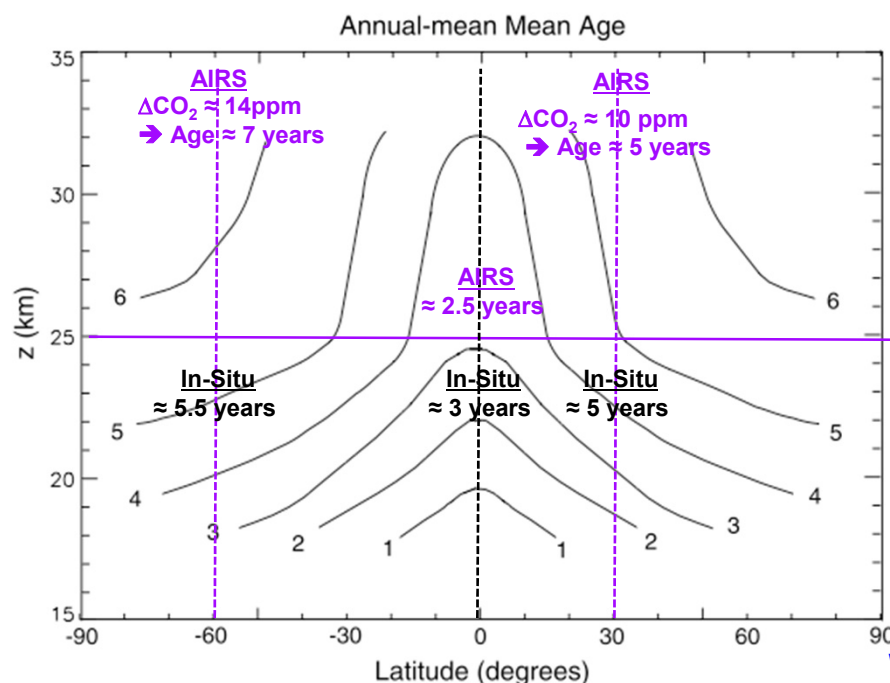
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# CO<sub>2</sub> Contrast due to Age of Stratospheric Air

The concentration of CO<sub>2</sub> in the stratosphere will be lower than in the troposphere by ~ 2 ppm for each year it lags behind due to interannual growth of tropospheric CO<sub>2</sub>



Waugh and Hall (2002), Age of stratospheric air: theory, observations and models, Rev. Geophys., 40, 1010, doi:10.1029/2000RG000101

## Age of stratospheric air vs latitude as a function of altitude

- In-situ observations only taken in NH, thus the schematic is symmetrical
- AIRS retrievals agree with in-situ measurements in NH and may indicate slight asymmetry (Waugh and Hall mirrored the NH result to the SH, where no data existed)



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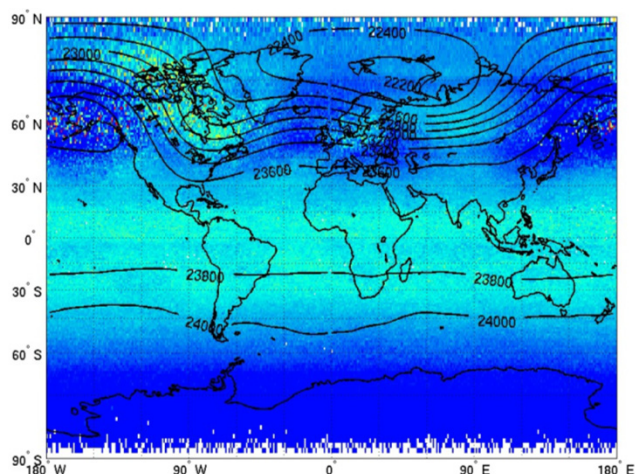
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# Stratospheric CO<sub>2</sub> Variation with Latitude (CO<sub>2</sub> after subtracting $\langle \text{CO}_2 \rangle$ for $|\text{lat}| \leq 4^\circ$ )

## Equator to Pole Contrast

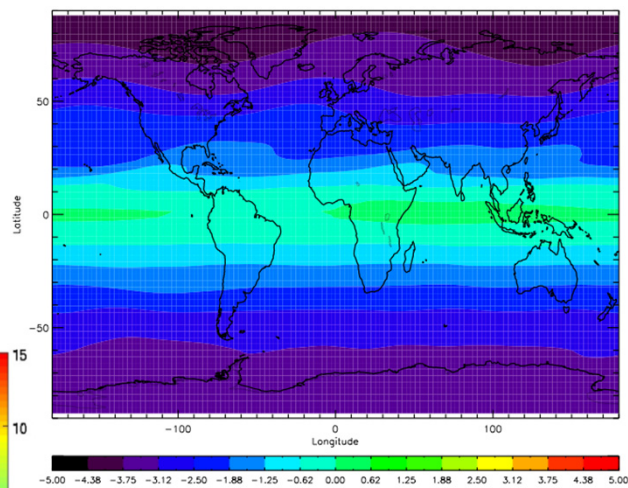
- Models show much lower contrast than AIRS and in-situ measurements

### AIRS



Color Bar Range : -15 to +15 ppm  
Range of Observed Variations: -10 to +5 ppm

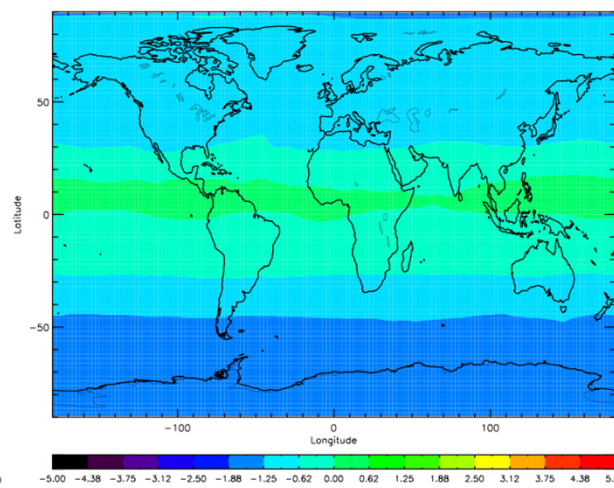
### 3-D IMATCH



Range of Variations: -5 to +2 ppm

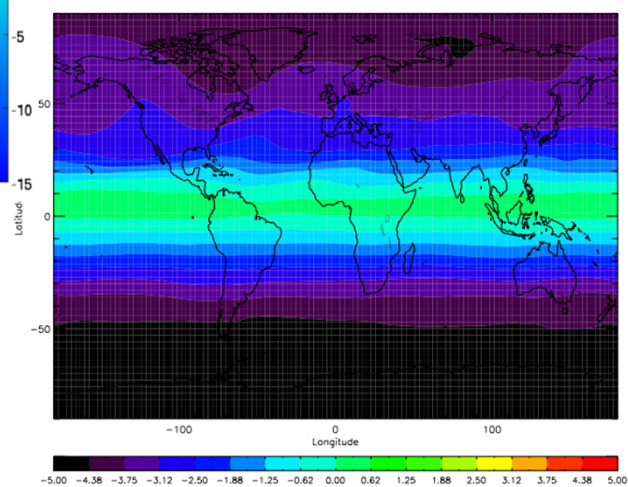
Color Bar Range: -5 to +5 ppm

### 3-D GEOS-Chem



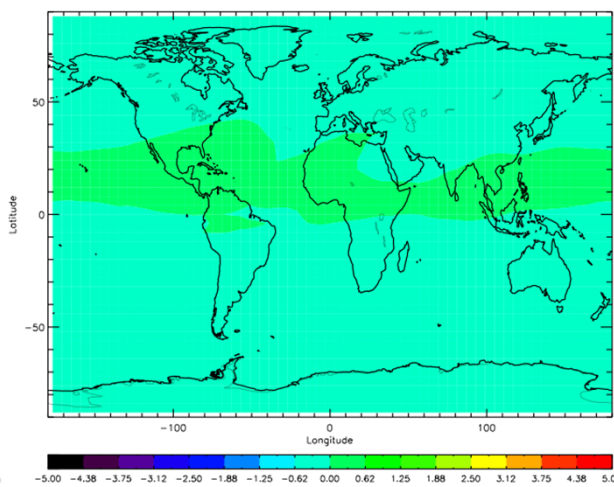
Range of Variations: -2 to +2 ppm

### 3-D MOZART-2



Range of Variations: -5 to +2 ppm

### 3-D Carbon Tracker



Range of Variations: -1 to +2 ppm



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# **AIRS First Results Lower-Tropospheric CO<sub>2</sub> (2.2km)**





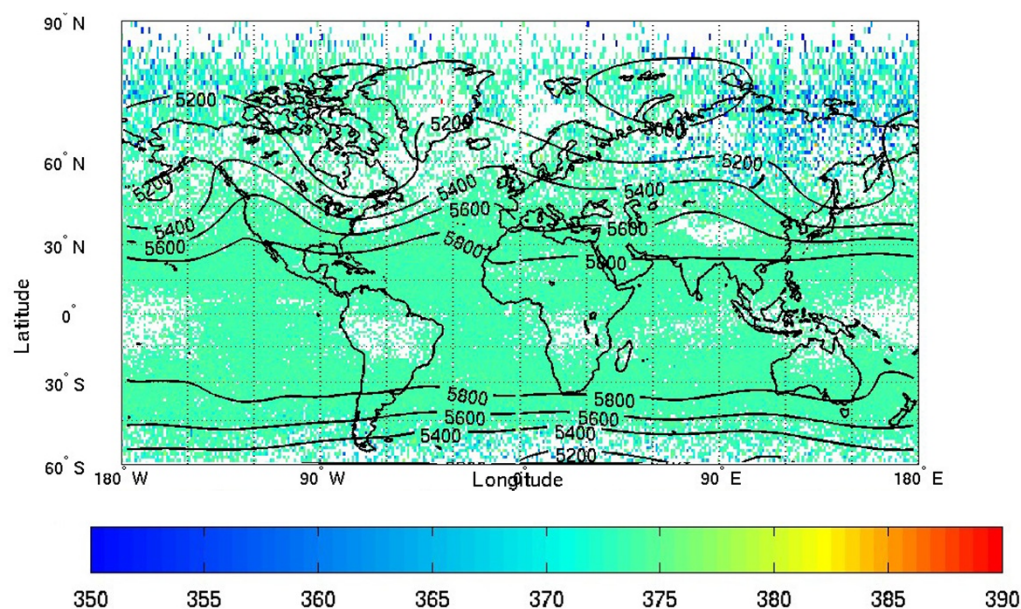
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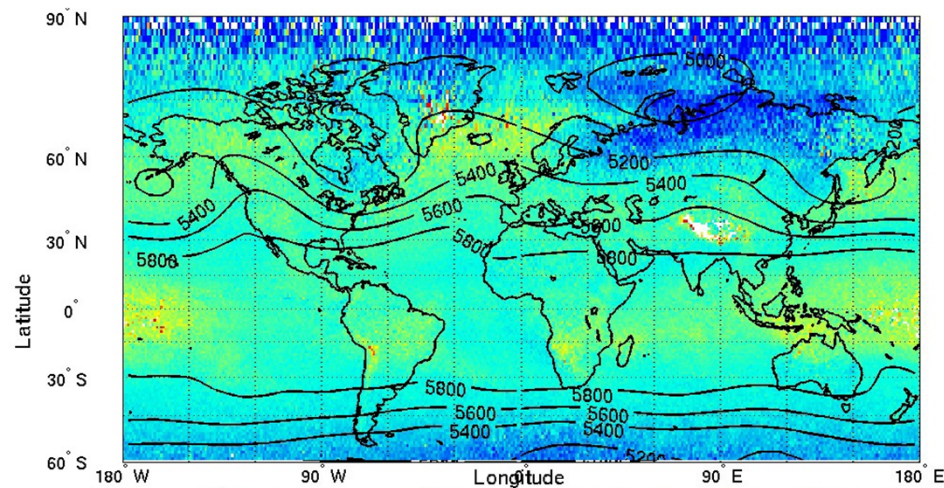
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## AIRS Lower-Trop (2.2km) vs Mid-Trop CO<sub>2</sub>

Mid-Trop - January 2003



Lower-Trop - January 2003



Surface Emission,  $E_s$ ,  
not yet implemented  
and no QA applied



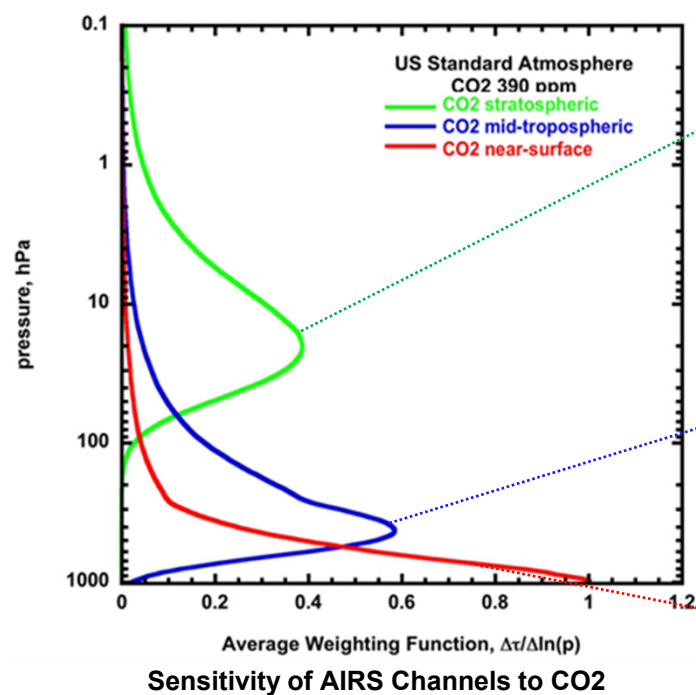
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## 3 Layers of CO<sub>2</sub> Derived from AIRS

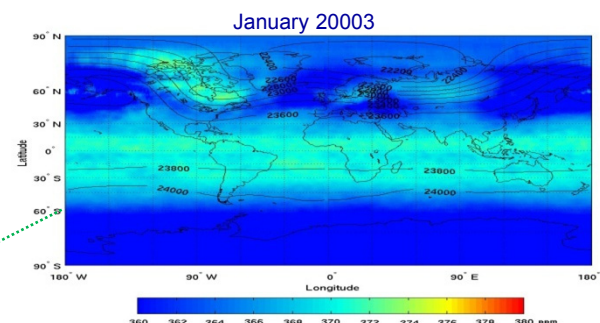
# Summary



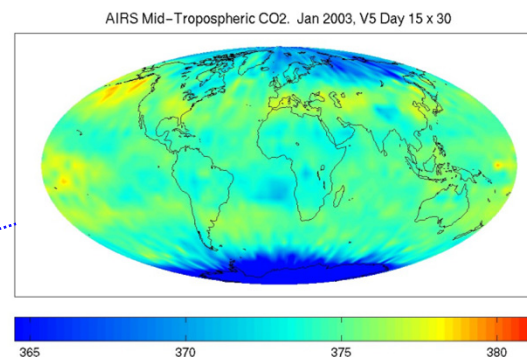
Stratosphere

Mid-Troposphere

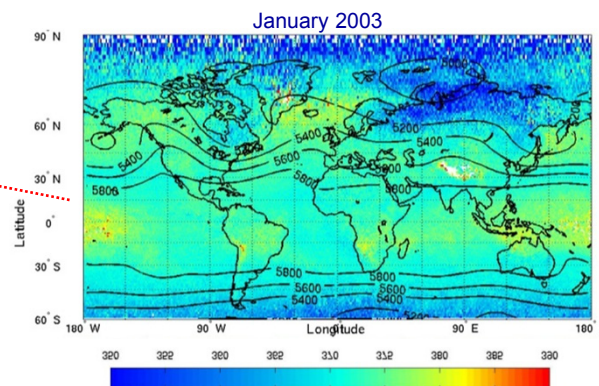
Lower Trop



Preliminary



Complete  
Sept 02 - Present



Preliminary





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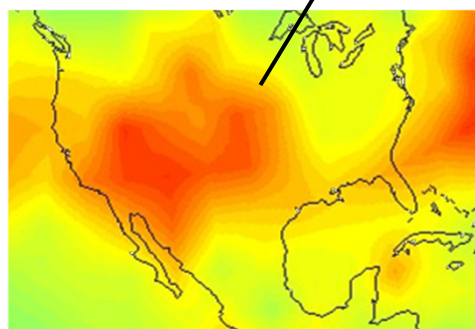
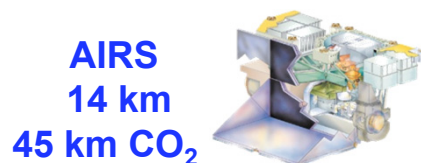
# ARIES can map GHG emissions from large cities and counties?

## ARIES Characteristics:

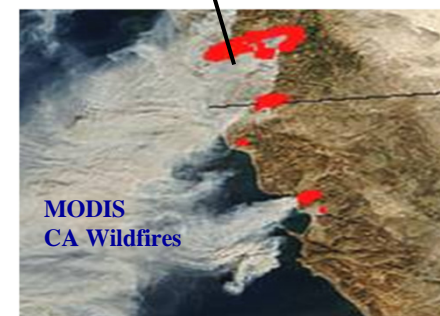
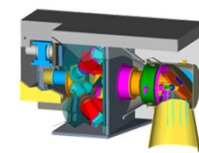
- Extension of AIRS Methodology
- Global Maps Daily ( $\pm 55^\circ$  Swath)
- Spatial Resolution: 2 km
- Spectral Range: 3.0 – 15.4  $\mu\text{m}$
- Spectral Resolution: 0.5  $\text{cm}^{-1}$

Over 5000 Channels

Products: Vertical Profiles of, T,  $\text{H}_2\text{O}$   
 $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{N}_2\text{O}$ ,  $\text{SO}_2$ ,  $\text{HNO}_3$ ,  $\text{O}_3$



AIRS  $\text{CO}_2$  Map, July 2003



ARIES  $\text{CO}_2$  Map Resolution

Products	IFOV (km)	$\lambda_1$ ( $\mu\text{m}$ ) $\nu_1$ ( $\text{cm}^{-1}$ )	$\lambda_2$ ( $\mu\text{m}$ ) $\nu_2$ ( $\text{cm}^{-1}$ )	R, $\Delta\nu$ ( $\text{cm}^{-1}$ )
Temperature, $\text{CO}_2$ , $\text{CH}_4$ , $\text{N}_2\text{O}$ , $\text{CO}$	1	3.39 2950	4.76 2100	2.0
Water, $\text{CH}_4$ , $\text{SO}_2$ , $\text{HNO}_3$	1	6.20 1613	8.70 1150	1.0
$\text{O}_3$ , $\text{HNO}_3$	1	8.70 1150	11.36 880	0.5
Temperature, $\text{CO}_2$	1	11.36 880	15.38 650	0.5



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**END**



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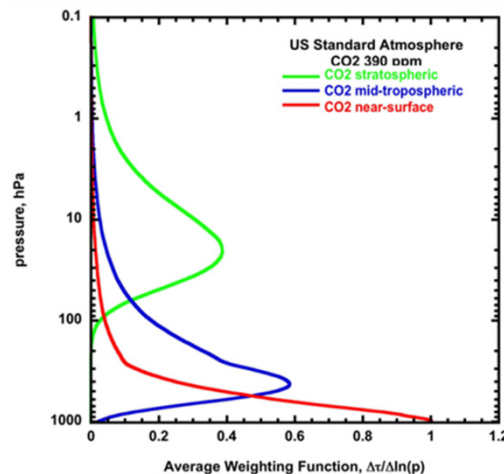
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## Factors Affecting the CO<sub>2</sub> Retrievals

v range:	Mid-Troposphere -10km	Stratosphere – 30km	Lower Trop – 2.2km
	13 CO <sub>2</sub> channels: 700 cm <sup>-1</sup> – 722 cm <sup>-1</sup>	17 CO <sub>2</sub> channels: 650 cm <sup>-1</sup> – 680 cm <sup>-1</sup>	10 CO <sub>2</sub> channels: 730 cm <sup>-1</sup> – 745 cm <sup>-1</sup>
$T(p)$	Strong	Very strong	Strong
O <sub>3</sub>	Strong	Weak	Medium
H <sub>2</sub> O	Medium	No impact	Medium
Surface emission, E <sub>s</sub> (T <sub>s</sub> , ε <sub>s</sub> )	Very weak	No impact	Medium
$\Delta G/\Delta \text{CO}_2^*$	~0.4	~0.2	~0.5

\*( $\Delta G/\Delta \text{CO}_2$ ) describes the sensitivity of observed spectra to changes in CO<sub>2</sub>. It is a function of the lapse rate of atmospheric temperature profiles which is 7 K/km in the mid-troposphere, 1.5K/km in the stratosphere and 10K/km near surface.



- **Mid-troposphere: Operational and Released to the Public (Sept 2002 – Present)**
- **Stratosphere: Algorithm Completed, QA and Validation Underway (8/2010)**
- **Lower troposphere: Algorithm Nearly Complete, Preliminary Retrievals Underway (12/2010)**

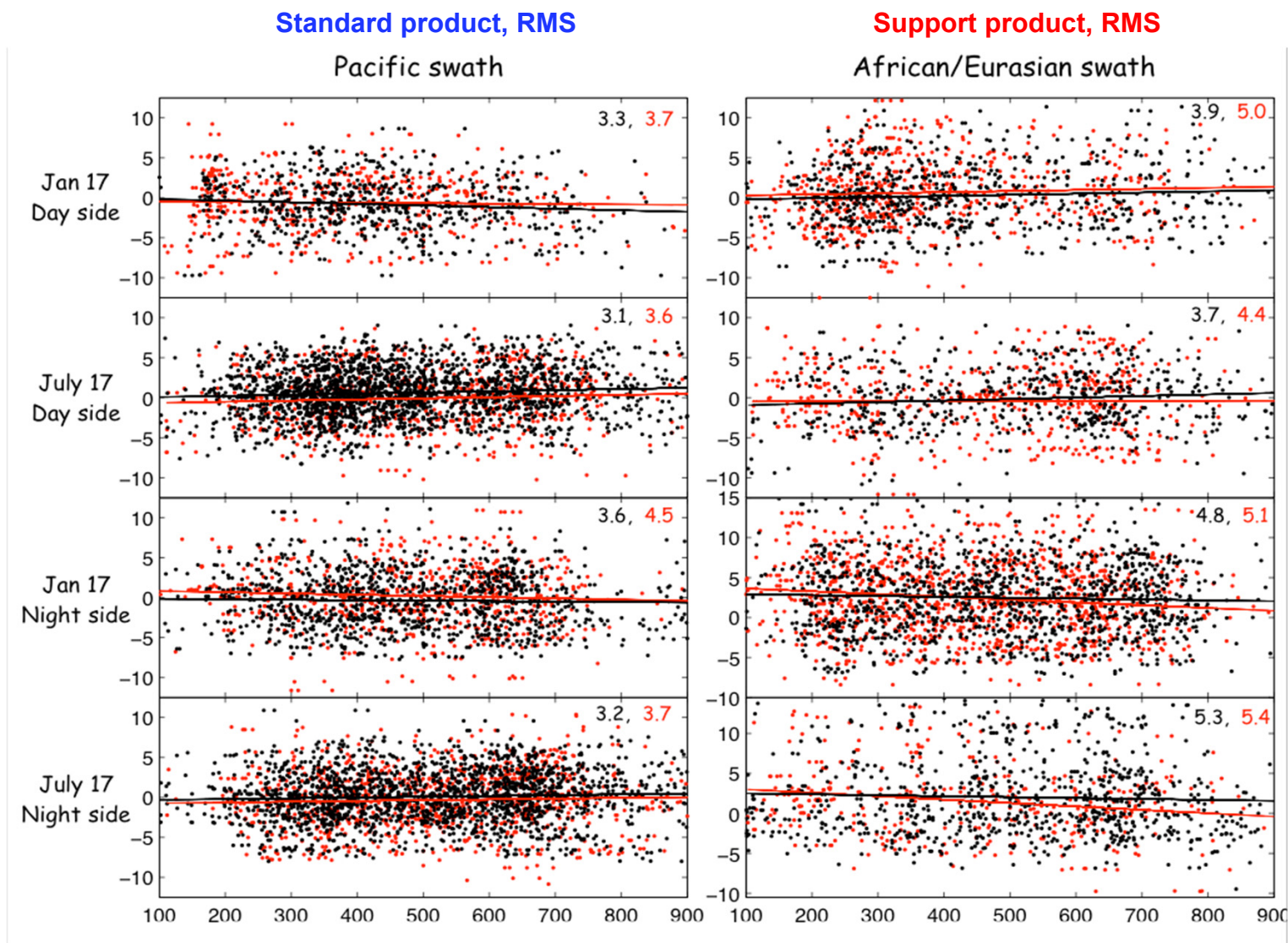


National Aeronautics and  
Space Administration

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California Institute of Technology  
Pasadena, California

**Atmospheric Infrared Sounder**

# AIRS - CarbonTracker upper-tropospheric CO<sub>2</sub> difference [ppm] vs. cloud top pressure eight N/S swaths, 2008



Davis Baker AGU 2010



National Aeronautics and  
Space Administration

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

*Atmospheric Infrared Sounder*

## Finding the LOCAL minimum on an N-Dimensional Surface According to Gauss, Lower Troposphere

The CO<sub>2</sub> retrieval is a post-processing algorithm applied after AIRS Level-2 product generation:

**Local Minimum:**  $\Theta_M, T^0(p), q^0(p), O_3^0(p), E_s^0(v)$

$$G^{(n)}(\mathbf{X}) = \sum_v \left[ \Theta_M(\mathbf{X}, v) - \Theta_C^{(n)}(\mathbf{X}, v) \right]^2$$

$$\frac{\partial G}{\partial X_{CO_2}} \rightarrow 0 \quad \text{Implemented}$$

$$\frac{\partial G}{\partial X_{T(p)}} \rightarrow 0 \quad \text{Implemented}$$

$$\frac{\partial G}{\partial X_q} \rightarrow 0 \quad \text{Implemented}$$

$$\frac{\partial G}{\partial X_{O_3}} \rightarrow 0 \quad \text{Implemented}$$

$$\frac{\partial G}{\partial X_{E_s}} \rightarrow 0 \quad \text{In Progress}$$





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**Atmospheric Infrared Sounder**

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L22803, doi:10.1029/2005GL024165, 2005

## On the determination of atmospheric minor gases by the method of vanishing partial derivatives with application to CO<sub>2</sub>

M. Chahine,<sup>1</sup> C. Barnet,<sup>2</sup> E. T. Olsen,<sup>1</sup> L. Chen,<sup>1</sup> and E. Maddy<sup>3</sup>

Received 22 July 2005; revised 3 October 2005; accepted 11 October 2005; published 18 November 2005.

[1] We present a general method for the determination of minor gases in the troposphere from high spectral resolution observations. In this method, we make use of a general property of the total differential of multi-variable functions to separate the contributions of each individual minor gas. We have applied this method to derive the mixing ratio of carbon dioxide in the mid-troposphere using data from the Atmospheric Infrared Sounder (AIRS) currently flying on the NASA Aqua Mission. We compare our results to the aircraft flask CO<sub>2</sub> measurements obtained by H. Matsueda et al. over the western Pacific and demonstrate skill in tracking the measured 5 ppmv seasonal variation with an accuracy of  $0.43 \pm 1.20$  ppmv. **Citation:** Chahine, M., C. Barnet, E. T. Olsen, L. Chen, and E. Maddy (2005), On the determination of atmospheric minor gases by the method of vanishing partial derivatives with application to CO<sub>2</sub>, *Geophys. Res. Lett.*, 32, L22803, doi:10.1029/2005GL024165.

## 2. General Approach

[3] We consider the radiative transfer equation

$$R(\nu) = S_s(\nu, \epsilon_s, \dots) + \int_{p_s}^0 B[\nu, T(p)] \left( \frac{\partial \tau(\nu, p, \langle \dots \rangle)}{\partial p} \right) dp \quad (1)$$

where  $R(\nu)$ , the outgoing radiance at frequency  $\nu$  measured at the satellite, is the sum of emissions from the surface and the atmosphere. Here  $\epsilon_s$  is the surface emissivity,  $B$  the Planck blackbody function,  $\tau$  the transmission function from any pressure level  $p$  to the top of the atmosphere and the angle bracket  $\langle \dots \rangle$  denotes a function of the profiles of temperature  $T(p)$ , water vapor  $q(p)$ , ozone  $O_3(p)$ , carbon dioxide mixing ratio  $CO_2(p)$ , etc. In this paper, we express the outgoing radiance  $R(\nu)$  in brightness temperature units,





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GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L17106, doi:10.1029/2004GL020141, 2004

## Midtropospheric CO<sub>2</sub> concentration retrieval from AIRS observations in the tropics

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Received 1 April 2004; revised 16 July 2004; accepted 2 August 2004; published 4 September 2004.

[1] Midtropospheric carbon dioxide (CO<sub>2</sub>) concentration is retrieved in the tropics (20S–20N), over sea, at night, for the period April to October 2003 from the Atmospheric Infrared Sounder (AIRS) observations. The method relies on a non-linear regression inference scheme using neural networks. A rough estimate of the mean precision of the method is about 2.5 ppmv (0.7%). The retrieved seasonal cycle and its latitudinal dependence agree well with aircraft CO<sub>2</sub> in situ measurements made at the same altitude range. Maps produced on a monthly basis at a resolution of 15° × 15°, although not yet fully understood, show good agreement with known characteristics of CO<sub>2</sub> distribution reflecting both atmospheric transport and surface fluxes (fossil fuel emissions, biomass burning, air-sea surface gas exchanges). INDEX TERMS: 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 0330 Atmospheric Composition and Structure: Geochemical cycles; 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing. Citation: Crevoisier, C., S. Heilliette, A. Chédin, S. Serrar, R. Armante, and N. A. Scott (2004), Midtropospheric CO<sub>2</sub> concentration retrieval from AIRS observations in the tropics, *Geophys. Res. Lett.*, 31, L17106, doi:10.1029/2004GL020141.

### 1. Introduction

[2] Knowledge of today's carbon sources and sinks, their spatial distribution and their variability in time is essential for predicting the future carbon dioxide (CO<sub>2</sub>) atmospheric concentration levels. The distribution of atmospheric CO<sub>2</sub> reflects both spatial and temporal evolutions as well as the magnitude of surface fluxes [Tans *et al.*, 1990]. In principle, it is thus possible to estimate these fluxes from atmospheric CO<sub>2</sub> concentration, provided that atmospheric transport can be accurately modeled. However, this approach is currently limited by the sparse and uneven distribution of the global flask sampling programs. Densely sampling the atmosphere in time and space, satellite measurements of the distribution of global atmospheric CO<sub>2</sub> concentration would in principle fill this gap in scale [Rayner and O'Brien, 2001].

[3] The feasibility of retrieving CO<sub>2</sub> and other trace-gas concentrations from space observations in the infrared has been demonstrated by Chédin *et al.* [2002, 2003] using the NOAA TOVS instruments. For the first time, 4 years of monthly mean midtropospheric CO<sub>2</sub> concentration were retrieved from TOVS infrared and microwave observations over the tropics (20S–20N) for the period July 1987–June 1991. A rough estimate of the method-induced standard deviation of these retrievals was of the order of 3 ppmv (less than 1%).

[4] With its 2378 channels covering most of the infrared spectrum at a very high spectral resolution, the Atmospheric Infrared Sounder (AIRS), launched onboard the NASA's Aqua platform in May 2002, gives the opportunity to use channels specifically sensitive to CO<sub>2</sub> and well covering the mid-to-high troposphere. Also flying onboard Aqua, the Advanced Microwave Sounding Unit (AMSU), with its 15 channels, provides microwave observations coupled with those of AIRS.

[5] Infrared CO<sub>2</sub> sensitive channels are also much more sensitive to temperature. Hence, the simultaneous use of infrared measurements, sensitive to both temperature and CO<sub>2</sub> variations, and of microwave measurements, only sensitive to temperature, allows separating these two effects.

[6] As compared to other regions, the tropics present a greater tropospheric temperature stability. Therefore, the separation between CO<sub>2</sub> and temperature variations is easier. The study is thus limited to the latitudinal band [20S–20N]. Retrieving CO<sub>2</sub> concentrations in the tropical zone is important for two reasons: the flask network is the least efficient in this part of the globe [Rayner and O'Brien, 2001] and the strong convective vertical mixing existing in the tropics rapidly transmits surface carbon flux variations to that part of the atmosphere seen by AIRS.

### 2. Data and Method

[7] A set of 43 AIRS channels, located in the two spectral bands where CO<sub>2</sub> is an absorber, near 15  $\mu$ m and 4.3  $\mu$ m, and presenting optimal properties to retrieve CO<sub>2</sub>, has been selected with the Optimum Sensitivity Profile (OSP) method [Crevoisier *et al.*, 2003a]. These channels are characterized by a strong sensitivity to CO<sub>2</sub> variations and a low sensitivity to other atmospheric components such as water vapor (H<sub>2</sub>O), ozone (O<sub>3</sub>), nitrous oxide (N<sub>2</sub>O), carbon monoxide (CO), and surface characteristics. They are part of the 324 AIRS channels distributed by NOAA/NESDIS [Goldberg *et al.*, 2003]. To design a method that may be used to process night-time as well as daytime observations, the channels located in the 4.3  $\mu$ m band, potentially contaminated by solar radiation, have not been selected for this study. Use is made of the eight AIRS channels 173, 175, 180, 185, 193, 213, 218 and 250. They are sensitive to CO<sub>2</sub> variations in the range 100–500 hPa (5–15 km), as shown by the corresponding 8-channel mean CO<sub>2</sub> Jacobian (partial derivative of the channel brightness temperature (BT) to a layer CO<sub>2</sub> concentration) plotted on Figure 1 for a representative tropical situation.

[8] The weakness of the signal induced on AIRS BT by CO<sub>2</sub> variations, associated with the complexity and non-linearity of the relationship between CO<sub>2</sub> concentration and

# Multiple Methods have been employed to Determine CO<sub>2</sub> from AIRS Observations

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D11301, doi:10.1029/2007JD009402, 2008



## CO<sub>2</sub> retrievals from the Atmospheric Infrared Sounder: Methodology and validation

E. S. Maddy,<sup>1</sup> C. D. Barnett,<sup>2</sup> M. Goldberg,<sup>2</sup> C. Sweeney,<sup>3</sup> and X. Liu<sup>1</sup>

Received 19 September 2007; revised 26 December 2007; accepted 30 January 2008; published 3 June 2008.

[1] In this paper we describe the methodology of an offline retrieval of CO<sub>2</sub> from AIRS data and show comparisons of these retrievals with all available NOAA ESRL/GMD aircraft data during 2005. In general, we find that when compared to the aircraft the AIRS CO<sub>2</sub> estimates agree to approximately  $\pm 0.5\%$  in middle-tropospheric CO<sub>2</sub> column abundances between  $\pm 65^\circ$  degrees latitude.

Citation: Maddy, E. S., C. D. Barnett, M. Goldberg, C. Sweeney, and X. Liu (2008), CO<sub>2</sub> retrievals from the Atmospheric Infrared Sounder: Methodology and validation, *J. Geophys. Res.*, 113, D11301, doi:10.1029/2007JD009402.

### 1. Introduction

[2] Although it was designed for high resolution/accurate temperature and moisture profiles, the National Aeronautics and Space Administration Earth-Observing System (NASA-EOS) Atmospheric Infrared Sounder (AIRS) is capable of measuring variations in carbon trace gases such as CO<sub>2</sub> [Chédin *et al.*, 2003; Crevoisier *et al.*, 2003; Engelen and Stephens, 2004; Amann *et al.*, 2005]. This capability coupled with the AIRS broad swath pattern, low and well characterized instrument noise, and global coverage afforded by a method termed cloud-clearing, enables derivation of the distribution of CO<sub>2</sub> (as well as other trace gas species) in the middle-to-upper troposphere on global scales twice per day.

[3] Numerous studies [Engelen *et al.*, 2004; Crevoisier *et al.*, 2004; Chahine *et al.*, 2005] have shown that retrievals from AIRS show expected seasonal and latitudinal variability in the tropics as compared to JAL Matsuda flask data [Matsuda *et al.*, 2002]. Engelen and McNally [2005] extend some of the results to higher latitudes using flask measurements from the National Oceanic and Atmospheric Administration (NOAA) Environmental Systems Research Lab/Global Monitoring Division (ESRL-GMD) formerly known as the Climate Monitoring Diagnostics Laboratory (CMDL) aircraft network. Nevertheless, attempts to use retrievals to constrain atmospheric inversions of CO<sub>2</sub> surface fluxes [Chevallier *et al.*, 2005] have been for the most part unsuccessful and comparison to models [Iverson *et al.*, 2006] have raised questions concerning the ability of models to correctly reproduce large scale circulation pathways of atmospheric CO<sub>2</sub> and other atmospheric trace species. Simultaneous derivation of atmospheric concentrations of CO<sub>2</sub>, CH<sub>4</sub> [Zhang *et al.*, 2006], and O<sub>3</sub> in the middle-to-upper troposphere as well as high vertical resolution

temperature and moisture profiles will enable better constraint on model transport and vertical mixing and warrant more study of the capabilities of the AIRS instrument in deriving CO<sub>2</sub> abundances.

[4] In this paper, we apply the methodology of Susskind *et al.* [2003] to the retrieval of CO<sub>2</sub> from cloud-cleared radiances. In the section 2 we describe the methodology of the NOAA algorithm, and in section 3, we compare these retrievals to an extended set of NOAA ESRL/GMD aircraft measurements obtained during 2005 (C. Sweeney, private communication, 2006).

### 2. AIRS CO<sub>2</sub> Retrieval

[5] The ability of a thermal sounder to measure variations in atmospheric CO<sub>2</sub> is highly dependent on its ability to separate the radiative effects of temperature and CO<sub>2</sub>. This is due to the fact that these sounders primarily use CO<sub>2</sub> absorption regions (e.g., 15  $\mu$ m, 4.3  $\mu$ m) for temperature sounding; thus errors in the CO<sub>2</sub> background used in temperature retrieval will propagate into the retrieved temperature profiles [Engelen *et al.*, 2001; Maddy *et al.*, 2005]. In fact, Divakarila *et al.* [2006] showed that biases in the Version 4 AIRS retrieved temperature profiles correlated very well with expected seasonal variability in CO<sub>2</sub>; however, the cause of the bias trend and seasonal oscillation is still under investigation.

[6] The AIRS instrument onboard Aqua is complemented with the Advanced Microwave Sounding Unit (AMSU), which utilizes an O<sub>2</sub> absorption band for temperature sounding. Ideally, the addition of the O<sub>2</sub> dependent microwave measurements to the CO<sub>2</sub> sensitive IR measurements will decouple the temperature/CO<sub>2</sub> interdependence; however, the low signal-to-noise ratio (SN) and sidelobe issues make the use of the microwave data problematic. In order to mitigate the interdependence between temperature and CO<sub>2</sub> for the AIRS data we added a covariance matrix (see Susskind *et al.*, 2003, equation (30a), equation (30b)) for the temperature retrieval and cloud-clearing steps. We retain both the diagonal and off-diagonal terms in order to preserve the channel correlation of a CO<sub>2</sub> perturbation. In

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D18302, doi:10.1029/2007JD009713, 2008



## A 4-year zonal climatology of lower tropospheric CO<sub>2</sub> derived from ocean-only Atmospheric Infrared Sounder observations

L. Larrabee Strow<sup>1</sup> and Scott E. Hannon<sup>1</sup>

Received 14 December 2007; revised 18 March 2008; accepted 29 May 2008; published 20 September 2008.

[1] A 4-year zonally averaged climatology of atmospheric CO<sub>2</sub> ocean only, within  $\pm 60^\circ$  latitude has been derived from the Atmospheric Infrared Sounder (AIRS) radiances. Using only very clear fields of view, the CO<sub>2</sub> profile in the computed radiances is scaled until agreement is found with observations. ECMWF forecast and analysis fields are used for the temperature profile in the computed radiances. The AIRS channels used to derive CO<sub>2</sub> amounts are nominally sensitive to CO<sub>2</sub> variability in the  $\sim 300$ –800 mbar region (2–9 km), significantly lower in the atmosphere than that in previous studies using AIRS. Validation using aircraft measurements of CO<sub>2</sub> at 650 mbar indicates that the AIRS CO<sub>2</sub> results presented here are accurate to the 0.5–1.0 ppm level. The AIRS-derived climatology clearly exhibits the CO<sub>2</sub> rectifier effect, with mean CO<sub>2</sub> values several parts per million lower than in those in the boundary layer. The AIRS CO<sub>2</sub> seasonal cycle has a relatively constant amplitude of  $\sim 3$  ppm from  $+10^\circ$  to  $+60^\circ$  latitude, which matches the boundary layer seasonal cycle amplitude near  $+10^\circ$  latitude but is about three times smaller than that in the boundary layer amplitude at  $+60^\circ$  latitude. Phase comparisons between the AIRS and boundary layer CO<sub>2</sub> seasonal cycles show the boundary layer phase leading AIRS in the Northern Hemisphere until  $\sim +10^\circ$  latitude, where the phases cross and the AIRS higher-altitude CO<sub>2</sub> begins to lead the boundary layer phase down to  $\sim -10^\circ$  latitude. These results may offer new insight into CO<sub>2</sub> interhemispheric transport. Growth rates derived from the AIRS CO<sub>2</sub> climatology are  $2.21 \pm 0.24$  ppm/year, in good agreement with in situ measurements.

Citation: Strow, L. L., and S. E. Hannon (2008), A 4-year zonal climatology of lower tropospheric CO<sub>2</sub> derived from ocean-only Atmospheric Infrared Sounder observations, *J. Geophys. Res.*, 113, D18302, doi:10.1029/2007JD009713.

### 1. Introduction

[2] Atmospheric CO<sub>2</sub> is the primary radiative forcing greenhouse gas, and its atmospheric growth rate has been rising steadily in the past few decades because of increasing global emissions [Raschke *et al.*, 2007]. Reliable estimates of climate change depend upon our ability to forecast atmospheric CO<sub>2</sub> concentrations, which requires knowledge of the CO<sub>2</sub> sources, sinks, and atmospheric transport. Inversion studies, [see, for example Denning *et al.*, 1995; Gurney *et al.*, 2003] generally use relatively sparse in situ boundary-layer CO<sub>2</sub> measurements, coupled with an atmospheric transport model to estimate source and sink regions and fluxes. Input data for these studies are relatively sparse, and heavily weighted to the Northern Hemisphere land sites. Constraining CO<sub>2</sub> sinks with existing data has been especially difficult since sinks involve large geographic areas, including the oceans. Moreover, transport of CO<sub>2</sub> from the boundary layer to the free troposphere is not well understood, but may be key for identification of sink regions.

[3] Physically accurate satellite measurements of CO<sub>2</sub> would greatly enhance our understanding of the global carbon cycle, by providing a much higher spatial and temporal data density. Profile information from satellite measurements may also be able to enhance the improvements discussed above by Stephens *et al.* [2007] and Yang *et al.* [2007]. Near infrared remote sensing of CO<sub>2</sub> can provide the

[4] Two very recent studies [Stephens *et al.*, 2007; Yang *et al.*, 2007] emphasized the importance of using information on the vertical extent of CO<sub>2</sub> to further constrain transport and flux models. Stephens *et al.* [2007] found that only three (out of twelve) TransCom 3 transport models [Gurney *et al.*, 2003] could closely reproduce the CO<sub>2</sub> vertical distribution derived from a rather limited number of aircraft flights. These three particular models predicted very different flux estimates than the other nine models, strongly suggesting a weaker northern uptake of CO<sub>2</sub> and weaker tropical emission than previous "consensus estimates".

[5] Yang *et al.* [2007] also found that the growing season net flux in the Northern Hemisphere is  $\sim 28\%$  larger than predicted by models using column-averaged mixing ratios of CO<sub>2</sub> and partial columns derived from aircraft profiles, rather than boundary layer values. They attributed this new result to their use of the column CO<sub>2</sub> as the primary measurement, since it is less sensitive to vertical mixing errors in the transport models.

[6] Sufficiently accurate satellite measurements of CO<sub>2</sub> would greatly enhance our understanding of the global carbon cycle, by providing a much higher spatial and temporal data density. Profile information from satellite measurements may also be able to enhance the improvements discussed above by Stephens *et al.* [2007] and Yang *et al.* [2007]. Near infrared remote sensing of CO<sub>2</sub> can provide the

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L17106

1 of 4

## ECMWF column estimation via 4D-Var data assimilation system

C. Crevoisier, Heilliette, S., Chedin, A., Serrar, S., Armante, R., Scott, N.A. (2004), Midtropospheric CO<sub>2</sub> concentration retrieval from AIRS observations in the tropics, *Geophys. Res. Lett.*, 31, L17106, doi: 10.1029/2004GL020141.

## NOAA regularized nonlinear least squares to minimize $\Sigma(\text{Obs}-\text{Calc})^2$

E.S. Maddy, Barnett, C.D., Goldberg, M., Sweeney, C., Liu, X. (2008), CO<sub>2</sub> from the Atmospheric Infrared Sounder: Methodology and validation, *J. Geophys. Res.*, 113, D11301, doi: 10.1029/2007JD009402.

## UMBC remaining radiance residuals for nighttime clear ocean fields

L. L. Strow, Hannon, S.E. (2008), A 4-year zonal climatology of lower tropospheric CO<sub>2</sub> derived from ocean-only Atmospheric Infrared Sounder observations, *J. Geophys. Res.*, 113, D18302, doi: 10.1029/2007JD009713.

D11301

1 of 7

D18302

1 of 20